BOUNDARY LAYER COHERENT STRUCTURES
AASERT SUPPLEMENT

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Final Report

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A MBL ARI Study

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Long Term Goals

It is apparent that a substantial portion of the air/sea fluxes of heat, moisture, and momentum is accomplished via intermittent processes (Khalsa and Greenhut 1985), processes that are rather poorly understood. Recently, Mahrt (1989) and Sikora and Young (1993) demonstrated that coherent structures in the marine boundary layer (MBL) are responsible for this flux-carrying intermittency. These coherent structure types include such secondary circulations as two-dimensional rolls (cloud streets), three-dimensional convective cells (thermals), and shear-driven eddies (billows) (Brown 1980). These features occur in different atmospheric boundary layer thermal stratification and shear regimes; some are forced primarily by thermal, and others by dynamic, mechanisms. Indeed, using the soaring patterns of birds, Woodcock (1975) determined the air/sea temperature differences and 10 *m* wind speeds typically associated with these two- and three-dimensional responses. Our ultimate research goal, then, is to determine the mechanisms underlying the intermittency in air/sea fluxes produced by these coherent structure types.

Scientific Objectives

In this study, we used a variety of complementary statistical/mathematical approaches to objectively identify the spatial and temporal characteristics of the coherent structure types. Our primary goal was to show that our approach could be used successfully to identify MBL coherent structures in LES data sets at either a fixed time (Rinker 1995; Rinker and Young 1996; Rinker *et al.* 1995; Rohrbach 1996; Rohrbach and Young 1996a,b) or at a fixed location (Winstead 1995; Winstead *et al.* 1995, 1996). To identify the spatial and temporal behavior of the coherent structure types, we chose obliquely rotated principal component analysis (PCA; Richman 1986). To capture the contribution of each coherent structure type to intermittency, we chose the recently proposed multiscale algorithm of Higuchi (1988). Our data sets were obtained using the high resolution output produced by the Penn State version of Moeng's Large-Eddy Simulation (LES) code (e.g. Schumann and Moeng 1991).

Approach

Principal component analysis has been shown to be capable of distinguishing and quantitatively describing multivariate structures within the atmosphere (e.g., Richman 1986; Preisendorfer 1988; White 1989; Alexander *et al.* 1993). Using both standard and newly developed PCA algorithms, we studied several three-dimensional LES data sets to see which principal components (coherent structure types) are largely independent of the large-scale forcing and which vary sensitively with it (Rinker 1995; Rinker *et al.* 1995; Rinker and Young 1996; Rohrbach, 1996; Rohrbach and Young, 1996a,b; Winstead 1995; Winstead *et al.* 1995, 1996). The velocity and buoyancy profiles of these components, together with their spatial distribution, internal dynamics, and regime dependence, were used to quantify the physical processes responsible for forming the different types of coherent structures.

In order to fully quantify the intermittency of coherent structure types, we also investigated their temporal behavior by studying the principal component scores, which were

obtained by projecting the unfiltered data set onto the dominant PCA vertical modes. In recent years, paradigms of complicated temporal behavior have been used as the basis for classifying the types of response that may occur in turbulent flows such as those found in the MBL (Henderson and Wells 1988). Nonperiodic, temporal variation is chaotic if the details of a particular time series can not be simulated beyond a few cycles with virtually identical initial conditions, a situation typical of most atmospheric flows. Analyses using the chaos measure introduced by Higuchi (1988) were performed on time series obtained from columns of LES data to simulate MBL measurements at a fixed location (Winstead 1995; Winstead *et al.* 1995, 1996). Both the original LES data sets and the coherent structure data sets given by the principal component scores were considered. By comparing the chaos measures given by these data sets, we identified the contributions of different types of coherent structures to the intermittency of the MBL.

Tasks Completed

Nathaniel Winstead used both power spectra and the multiscale algorithm of Higuchi (1988) to study principal component scores obtained from an LES time series at a virtual tower (i.e., a time-height section) in the LES grid. He demonstrated that both approaches can be used to identify the principal component vertical profiles composing each stage within the lifecycle of convective coherent structures (Winstead 1995; Winstead *et al.* 1995, 1996).

Don Rinker, Joe Rohrbach and Todd Sikora applied the obliquely rotated PCA algorithm to three-dimensional multivariate snapshots of LES data and found that while the structure and dynamics of three-dimensional convective cells were not strongly dependent on forcing intensity, their occurrence was strongly regime dependent (Rinker 1995; Rinker *et al.* 1995; Rinker and Young 1996; Rohrbach, 1996; Rohrbach and Young, 1996a,b). For high-shear environments, the three-dimensional convective cells were partially supplanted and highly modified by two-dimensional convective rolls (Rinker 1995; Rinker *et al.* 1995; Rinker and Young 1996; Rohrbach, 1996; Rohrbach and Young, 1996a,b). Moreover, a smaller scale, quasi-two-dimensional coherent structure, low momentum updraft streaks, were observed in the surface layer of the roll updrafts. The streaks and three-dimensional convective cells were linked in this regime (Rohrbach, 1996; Rohrbach and Young, 1996a,b). In contrast, in very low shear environments, some of the three-dimensional convective cells began to rotate around their vertical axis via mechanisms similar to those observed in tornadic thunderstorms (Rohrbach, 1996; Rohrbach and Young, 1996a,b).

Results/Conclusions

The application of the PCA algorithm to idealized data tests has shown that the method is able to distinguish multiple, simultaneously occurring, coherent structure types under several realistic conditions. These tests provide proof that PCA can yield valid results without having an *a priori* conceptual model, as required of previous (conditional sampling) methods. Analysis of fields of multivariate profiles from LES data sets reveals that the various forms of mixed-layer convection can be separated from gravity waves of the free atmosphere (Rinker 1995; Rinker *et al.* 1995; Rinker and Young 1996). Score maps produced by these analyses were used to

document the regime-dependent spatial form of these coherent structures (Rinker and Young 1996). Rohrbach (1996) and Rohrbach and Young (1996a,b) used these height-dependent score maps to diagnose the regime-dependent dynamics of the primary coherent structure types including two-dimensional roll vortices, two-dimensional surface-layer wind streaks, three-dimensional thermal convection, and vertically oriented convective vorticies.

Winstead (1995) and Winstead *et al.* (1995, 1996) documented the vertical profiles and temporal behavior of two- and three-dimensional thermal structures using the Higuchi algorithm applied to PCA score series of LES data. Analysis of the MBL ARI field program tower observations using the methods pioneered on simulated towers by Winstead (1995) and Winstead *et al.* (1995, 1996) yielded the temporal variability and spatial structure of the observed eddies.

Impact for Science

The observational and modeling studies completed in this study will lead to improved understanding of the flux intermittency commonly observed in the MBL. This will help advance our overall understanding of processes that affect the state of the sea surface. Furthermore, this increased understanding has demonstrated some strong dynamic similarities between the coherent structures responsible for this intermittency and the more widely studied mesoscale convective systems.

Relationships to Other Programs or Projects

Our work using LES data was made possible through our close collaboration with our colleague Prof. John Wyngaard, who is also supported by the MBL ARI. The work performed by us on this ARI project was closely related to our work performed on our HI-RES project (June 1, 1990-September 30, 1995), in which we determined the stress variability at the sea surface caused by the boundary layer coherent structure types of two-dimensional rolls and three-dimensional cells. As this stress variability is produced by intermittent vertical momentum transports by these coherent structures, better understanding of the sea surface stress patterns requires a better understanding of the actual momentum transports by these structures.

Transitions Accomplished or Expected

Improved understanding of air/sea flux intermittency will undoubtedly lead to improved means for interpreting sea surface roughness patterns on SAR imagery. In 1996, the PIs and two individuals funded by this AASERT project (Todd Sikora and Nathaniel Winstead) began collaborative work with Don Thompson and Robert Beal of JHUAPL on a new ONR project to derive from SAR imagery quantitative estimates of boundary layer depth, surface wind speed and direction, and air-sea fluxes.

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Rohrbach, J.W. and G.S. Young, 1996b: The dynamics and three-dimensional structure of the coherent eddies of the boundary layer investigated through principal component analysis. Part II: rotating thermals. Submitted to *J. Atmos. Sci.*

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PUBLICATIONS/PRESENTATIONS/REPORTS
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Journal Articles

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Rohrbach, J.W. and G.S. Young, 1996a: The dynamics and three-dimensional structure of the coherent eddies of the boundary layer investigated through principal component analysis. Part I: rolls and streaks. Submitted to *J. Atmos. Sci.*

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